DR STEF FEIJEN (Orcid ID : 0000-0002-7201-3455)
MR KEVIN KUPPENS (Orcid ID : 0000-0003-4592-5974)

Article type : Review Article

Monitoring the swimmer's training load: a narrative review of monitoring strategies applied in research

Stef Feijen[1], Angela Tate[2], Kevin Kuppens[1], Lorna A. Barry[3], Filip Struyf[1]

[1]Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, University of Antwerp, Belgium

[2]Department of Physical Therapy, Arcadia University, Glenside, PA.

[3]Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland

RUNNING HEAD: Monitoring strategies in competitive swimming

Corresponding author: Filip Struyf, Faculty of Medicine and Health Sciences, University of Antwerp, Belgium; Universiteitsplein 1, 2610 Wilrijk, Belgium; Filip.struyf@uantwerpen.be

Word count: 3202

Abstract word count: 219

Number of tables: 1

Number of figures: 0

ACKNOWLEDGEMENTS

N/A

Funding

No funding was received for the preparation of this manuscript.

CONFLICTS OF INTEREST

There are no conflict of interest to declare.

ABSTRACT

The high incidence of injury during swim-training as well as the increasing demands of the sports make monitoring of the swimmer's training load a key concept requiring further investigation. Research has previously introduced numerous methods for the purposes of monitoring the swimmer's training load, but a narrative review discussing the strengths and limitations of each method is lacking. Consequently, this narrative review aims to summarize the monitoring strategies that have been applied in sports medicine research on competitive swimmers. This knowledge can assist professionals in the field in choosing which method is appropriate in their particular setting. The results from this study showed that external training load was predominantly obtained through real-life observation of the swimmers' training volume. However, research has investigated a number of internal load monitoring tools, including blood lactate, training heart rate and perceived effort of training. To date, blood lactate markers are still considered most accurate and especially recommended at higher levels of competitive swimming or for those at greater risk of injury. Further, mood state profiling has been suggested as an early indicator of overtraining and may be applied at the lower competitive levels of swimming. Professionals in the field should consider the individual, the aim of the current training phase and additional logistical issues when determining the appropriate monitoring strategy in their setting.

Keywords: Swimming; Review; Load monitoring

INTRODUCTION

Since the establishment of the Olympic Games in 1896, competitive swimming has grown to become one of its largest disciplines.[1] As a result, its competitive level has increased accordingly but this requires the swimmers to prepare differently for major swimming events. Modern swim-training programs are now characterized by year-round swimming with little time for off-season recovery.[2,3] In fact, these training programs seem inherently volume dependent, with elite athletes swimming up to 57.1 kilometres per week.[4]

Swim-training programs primarily aim to induce adaptations to the body that allow the swimmer to perform better in competition[5] but this requires a carefully pre-determined combination of training intensity, volume and rest.[6] However, researchers have suggested that swimmers train too much according to their capabilities[3,4,7] and that they restrain their body from sufficient rest and recovery that is required for optimal adaptation.[8] During their 10- to 15-year careers, swimmers frequently practice up to seven days per week,[3] logging between 10.000 and 14.000 metres.[2] This excessive exposure to swimming has been linked to overtraining[9] and increases the risk of soft-tissue injury, pain and dissatisfaction.[3,7,10] Shoulder pain is particularly frequent[11,12] and, with prevalence rates reported as high as 91%,[7] is a major cause of missed practice.[13]

Injuries in competitive swimming hence appear to primarily arise from repetitive strain and microtrauma during periods of excessive training.[10,14] Athletic trainers have reported treating a higher percentage of swimmers with shoulder pain during the (pre-competitive) training season, in which athletes swim greater volumes to gain strength and power.[10] In addition, in a prospective study conducted at the 2016 Olympic Games, swimming was found to be the only sport in which the incidence of injury was significantly higher in training compared to competition.[15]

The establishment of a high injury incidence as well as the increasing demands of swim-training programs make monitoring of the swimmer's training load a key concept requiring further investigation.[16] The competitive swimmer's training load units can be thought of as either external or internal.[17] External load refers to the actual work completed by the athlete[17,18] and provides valuable information in determining the swimmer's capabilities. However, coaches frequently prescribe these loads regardless of the athlete's individual characteristics[19] and these seem to play an important role in how the athlete perceives and, subsequently, adapts to training.[20] The internal load, or the relative physiological, psychological and biomechanical stress imposed on the athlete[17,18] is also critical in determining the training load.[18] Even more so, this combination of external with internal load has been suggested to aid in revealing fatigue or in identifying periods when the athlete might be more prone to injury.[21,22]

Previous research has introduced a number of methods to quantify either the external or internal load of swim-training. However, this variety of available methods makes it difficult for the end-user to choose which is appropriate in their particular setting[23] and a narrative review discussing the strengths and limitations of each method is lacking. Consequently, this study aims to summarize the monitoring strategies that have been applied in sports medicine research for the purposes of quantifying the swimmer's training load.

METHODS

This narrative review was reported following the IMRAD (introduction, methods, results, discussion) format.[24] Although this study was qualitative of design, we used a systematic search and screening strategy to identify relevant literature. PubMed, Web Of Science and Sport Discus databases were searched using combinations of the terms covering the topics of *competitive swimmers* (*swim* OR swimmer OR swimming*) AND *monitoring* (*monitor or track or observe or record or measure*) AND *training load* (*training volume or training load or exercise or practice or training program OR workload OR training intensity OR physical exertion*). The search was performed by two researchers (N.D and T.D) up to January 2020. No limits were used for age or competitive level. Studies that longitudinally assessed at least one parameter of external or internal load were considered eligible for inclusion. Case-studies and systematic reviews were excluded. Studies conducted on synchronized swimmers, water polo players and triathletes were also excluded. Two reviewers (N.D and T.D) independently assessed the articles for eligibility based on evaluation of first the title and abstract and second the full text. Finally, data related to (1) the investigated parameter of training load and (2) the method of monitoring were extracted from the included studies.

RESULTS

Electronic database and manual searches returned 792 results. Screening excluded 764 articles, mainly because populations other than competitive swimmers were included. Finally, data was extracted from 28 eligible studies. Authors of 19 out of the 28 studies reported monitoring parameters of both external and internal training load simultaneously. Three studies assessed external training load,[10,25,26] whereas seven studies exclusively investigated parameters of internal load.[27-33] The monitoring methods are listed in table 1.

External training load

External parameters of training load were monitored in 19 out of 28 studies. Swimming volume was typically obtained and reported as the average distance[10,25-27,34-45] or duration [37,39,44,46,47] swam per week or per year. A number of studies also reported the volume of dry-land exercise in hours per week[34,35,38,40]. External load parameters were either observed in real-life by the coach or researcher[10,25-27,34-37,39-45,48-50] or obtained through self-reported questionnaires during the study.[46,47]

Internal training load

Physiological markers

Physiological markers were used either to provide an average measure of training over time (incremental testing) or to monitor a training session in progress.[51] Blood lactate concentration (LA) has particularly been obtained. In these studies, researchers measured LA immediately after a workload session either by taking fingertip[27,34-36] or earlobe[28,30,31,42,50] blood samples. Although frequently monitored, most of the studies measuring LA solely used this parameter as a criterion value to determine the validity and reliability of other markers in estimating the internal training load[27,30,34-36,42], whereas only few studies applied LA profiling across the season to assess the swimmer's individual fitness level and monitor training-induced changes.[28,31] Much of this work paid particular attention to the lactate threshold (LT) which has been variously defined as maximal lactate steady-state or fixed blood lactate level and refers to the maximal exercise intensity that can be maintained without lactate increasing exponentially.[52-54]

Training heart rate (HR) has also been used to monitor the internal load of a swim-training session.[29,30,36,42] HR monitoring reflects a general overall body response to stress but does not necessarily tell us what is happening in the muscles or energy systems.[8] In swimming research, traditional tracking devices were applied immediately after a swimming session to monitor the swimmer's HR. However, similar to LA monitoring, these measures of HR were mainly obtained as a criterion value to determine the validity and reliability of alternative methods in estimating the training intensity.

Alternatively, a number of investigations have used a pre-study incremental swimming test in which the response to progressive, incremental swimming was evaluated.[54] In these studies, researchers first assessed the relationship between swimming pace and measures of HR or LA and then estimated the intensity of the training session based on the volumes that had been swum at a specific pace.[38,40,41,45,49]

Finally, several subjective markers have been investigated for their use as an indirect measurement of the training intensity. The 15-grade scale (6-20) for rating of perceived exertion (RPE)[55] is such a marker which allows the athlete to rate its own perception of endured stress and effort during training based on a single rating. The session-RPE (sRPE) is a similar subjective marker, which is based on the RPE-scale and was proposed to further simplify the quantification of training load.[56] The sRPE is expressed in arbitrary units (AUs) and is calculated by multiplying the category ratio (CR-10) RPE score,[57] which is obtained 30 minutes after the training session, with the duration of the training.[56] Previous research has confirmed the validity of both RPE[29,30,58] and sRPE[42] as measures of exercise intensity during swimming. However, as yet its use in competitive swimming remains rather limited.[32,37,39,43,44,46,48]

Psychological markers

Psychological markers of training load were assessed in the literature using a number of questionnaires. These include the Profile of Mood States (POMS)[59,60] and the 19-item Training Distress (TDS)[61] scale. The POMS focuses on mood disturbance as an indicator of training load[59] and describes six dimensions of the construct "mood"; anger, confusion, depression, fatigue, tension, and vigor. Although its validity in assessing the training load has been confirmed,[62] only one study reported using this questionnaire for such purposes in a competitive swimming setting.[46] Another approach to psychological monitoring of the training load involves the use of symptom checklists.[33,47] One study investigated the swimmers' training distress over a 2-week training period by asking participants to complete the TDS scale[61] prior to every evening session. The TDS investigates a variety of symptoms such as emotionality, general fatigue, concentration difficulties, physical discomfort, sleep disturbance and appetite changes that are likely to be representative of athlete's experiences during acute overload.

DISCUSSION

We aimed to summarize the methods that have been used in sports medicine research for the purposes of monitoring the swimmer's training load. Knowledge of the inherent strengths and limitations of these monitoring strategies can aid professionals in the field in choosing which method is appropriate in their setting. The literature search resulted in 28 eligible studies. Studies that included external parameters typically monitored the swim-training volume through direct observation of the training session in real-life.[10,25-27,34-37,39-45,48-50] Internal load was investigated in 23 studies. Nine studies reported physiological measures of blood lactate[27,28,30,31,34-36,42,50], whereas four studies assessed the training heart rate.[29,30,36,42] Authors of seven out of the 28 studies reported using questionnaires of perceived exertion[32,37,39,43,44,46,48], whereas another three studies monitored training load through psychological parameters.[33,46,47]

Interpretation and exploration of the findings

To our knowledge this is the first synthesis of the literature on monitoring strategies in competitive swimming. Our findings highlight that although investigators frequently obtained training data in real-life, there is still plenty of research that reported the use of cross-sectional questionnaires for monitoring the swimmer's external training load.[3,7,63-66] However, this data is arguably biased by social desire, individual differences and seasonal variations in the sport,[18,67] whereas real-life observation provides a more valid measurement of the athlete's actual work.[68,69] Based on the literature, we advise to monitor the swimmer's external load in real-life whenever a reasonably small number of swimmers are to be studied or coached. However, epidemiological research often requires larger populations to draw significant conclusions.[68] In such a setting real-life monitoring may no longer be cost-effective, hence questionnaires may be the only available method.[70-72] Alternatively, certain upcoming global positioning tracking systems (GPS) have already been suggested a 'game-changer' in this area and may aid in the conducting of long-term observational studies in large groups of swimmers.[73]

Many sport scientists agree that the sum of training stressors should be monitored to obtain a comprehensive understanding of the impact of training.[74] One interesting finding of our study is that although psychological markers have not frequently been used in a swimming setting, investigators have recently suggested that continuous psychological profiling can aid in determining poor recovery state and prevent overtraining.[60,75] The POMS is one of the few tools used in competitive swimming which has also been considered an effective and reliable warning of overtraining.[75-77] This questionnaire represents the athlete's mood either by an iceberg or inverted iceberg profile, which refers to a successful athlete or one at greater risk of overtraining, respectively.[78] Although this connection has been shown reliable in a variety of sport contexts, including swimming,[47] it should be acknowledged that as with any other psychological testing, the POMS may not be suitable for all swimmers because of the intra-individual differences between the athletes. Nevertheless, many competitive swimmers face the continuously growing pressure to perform because of the increasing popularity and competitive level of the sport.[15,79] Failure to cope with these stressors may result in burn-out or other disorders that can significantly decrease performance or increase the swimmer's susceptibility to injury.[80] These findings make psychological profiling require more attention in research. Based on the literature, a cross sectional assessment of the POMS will only provide little information and we recommend multiple measurements across the season and advise to complement these tests with similar tools such as the TDS scale.

The results of this study also draw special attention to the Rating of Perceived Exertion (RPE) marker. This RPE scale appears to be gaining momentum in research due to its promising correlations with training HR and LA.[30,81,82] In addition, the RPE has been found valid for determining the swimmer's internal training load.[32,37,39,43,44,46,48] Although RPE measurements have shown potential for evaluating the training stress in high-intensity exercises such as swimming[81,83,84], its use may still be restricted due to the complex interaction of many factors that contribute to the personal perception of physical effort.[85] Investigators, therefore, recommend to complement the RPE with an objective assessment of internal training load.[22,74,86]

Findings of our study highlight that both HR and LA were predominantly used as an objective assessment of the swimmer's training intensity. Training HR has been found to be valid[87] and reliable[88] in steady-state training sessions but is deemed rather inaccurate in a setting characterized by fluctuations in intensity (eg, competitive swimming). In contrast, LA measurements are considered more accurate in determining the training intensity as they allow assessment of the real workload of an exercise on the muscle.[8] Most of the studies included in our review have monitored LA either by fingertip[27,34-36] or through earlobe[30,42] measurements. These procedures have become fairly easy to perform over the past few years[18], however, it is the interpretation of LA measurements that remains rather complex[8]: lactate is produced during the anaerobic (eg, oxygen-independent) metabolism of glucose,[89] which is of particular importance during short-duration exercise at high intensity.[54,89,90] During exercise, LA will accumulate only when its rate of efflux from the working muscles to the blood exceeds its removal to carbon dioxide.[90] This mechanism suggests that the concentration of LA is a good indicator of the muscles' capacity for an athletic performance[8] which allows coaches to tell what physiological adaptation has taken place over time. An increase in LA for the same training stimulus may, for instance, point to an increased anaerobic metabolism and therefore higher levels of LA at slower speeds, which may be indicative of impending overtraining.[8]

The usefulness of LA measurements and the frequency with which it should be applied may ultimately depend on the swimmer's competitive level. Its complex interpretation require LA measurements to be performed exercise-specific, even to the specific stroke one would use the information for. This means that for a young low-level competitive swimmer, who focuses more or less on improving the swimming technique, a few lactate tests per year may be sufficient to characterize his or her physiological profile and provide an appropriate training framework. However, at higher competitive levels we advise a more accurate monitoring of the training load and recommend LA tests to be scheduled at least every few weeks, with supplemental measurements performed during training.[8]

Finally, immuno-biological parameters such as parameters associated with hormonal regulation, or lymphocytes and cytokines have generally shown promising results as objective indicators of overtraining in a variety of sport contexts.[76,91] However, the limited research on competitive swimmers did not show any significant training-induced changes in immunological parameters.[92] Measures of salivary proteins such as alpha-amylase (sAA) and salivary nitrite (sNO2) did, however, show proportional responses to varying intensities and loads in swimmers.[36,93] In addition, recent research has shown real-time analysis of sAA[94] to be a valid method for determining the exercise intensity in swimming.[34,35] Given the results of these studies, biological parameters may arguably grow to become standard monitoring strategies in a swimming setting but until then further research is necessary before these markers can be implemented.

Limitations and recommendations for future research

There are some limitations that should be acknowledged. First and foremost, the non-systematic nature of this study limits generalizability of our results. Additionally, there is no consensus on the standard structure of reporting narrative reviews,[24] which is a major limitation of our study methodology and restricts us from providing strong recommendations for practice. Nevertheless, narrative research applying the methodological rigour of systematic reviews is still considered the cornerstone for synthesis of medical literature,[24] which was the primary aim of this study.

This review focused solely on those monitoring strategies that were applied in an observational setting. Although alternative methods such as the training impulse measurement[44], oxygen measurements[95] or the wingate test for anaerobic capacity and power[96] may provide additional information regarding training management, these methods have not been widely used in a longitudinal research setting involving competitive swimmers. In addition, the more invasive nature, complex calculations or logistical difficulties of these methods may limit their use in a practical setting. Additional parameters such as stroke length, stroke rate and the prevalence of biomechanical errors in swimming stroke may be assessed to improve the swimmer's propulsive efficiency while also decreasing the risk of injury. [97] However, the benefits of such parameters are hard to obtain when faced with large groups of swimmers. Tools such as complex video analysis and accelerometers can aid in monitoring these stroke parameters but these methods need further research before they can be implemented.[98]

Psychological profiling may be another powerful tool with great potential in managing one's own training program, particularly when combined with biological markers such as hair cortisol levels for the control of chronic stress[99,100] or cytokine profiling for the detection of overtraining and injury.[91,101,102] Future research is needed to validate sport-specific psychological assessment tools that allow for regular and comprehensive mental health profiling of the swimmer. Finally, the scientific understanding regarding the magnitude of change that is clinically meaningful for a specific training load variable is still limited, yet essential for informed decision making. Practitioners have been recommended to limit increases in weekly training load to <10% to minimize the risk of injury.[9] Similarly, future research should investigate the potential of reducing the overall training volume of competitive swimmers while maintaining a high performance level.

CONCLUSION

The aim of this study was to summarize the literature investigating monitoring strategies in competitive swimming. Real-life observation of external training load is recommended but should be complemented with at least one measure of internal load. The POMS or RPE may be useful as early indicators of overtraining at lower levels of swimming, however, we advise regular lactate profiling in swimmers who are at increased risk of overtraining or in those exposed to greater training loads. Finally, professionals in the field should consider the individual, the aim of the current training phase and additional logistical issues in determining which monitoring strategy is appropriate in their setting.

PERSPECTIVES TO SPORTS MEDICINE

Accurate monitoring of the athlete’s training load is a key concept for optimizing performance while reducing the risk of injury. The increased risk of injury and overtraining due to the high volumes of swimming has for long been a hot topic among swimming athletes, coaches and sport scientists. In fact, competitive swimming is in need of practice guidelines to reduce injury, but none exist. Monitoring the training load has gradually been incorporated in research but a comprehensive overview summarizing the available methods and discussing their inherent strengths and weaknesses is lacking. The findings of this study may aid clinicians working with the swimmer in determining which monitoring strategy is appropriate in their specific setting and, subsequently, enhance monitoring across the field.

REFERENCES

1. Nugent FJ, Comyns TM, Burrows E, Warrington GD. Effects of Low-Volume, High-Intensity Training on Performance in Competitive Swimmers: A Systematic Review. *J Strength Cond Res.* 2017;31(3):837-847.
2. Pink M, Tibone J. The painful shoulder in the swimming athlete. *Orthop Clin North Am.* 2000;31(2):247-261.
3. Tate A, Turner GN, Knab SE, Jorgensen C, Strittmatter A, Michener LA. Risk Factors Associated With Shoulder Pain and Disability Across the Lifespan of Competitive Swimmers. *J Athl Train.* 2012;47(2):149-158.
4. Feijen S, Tate A, Kuppens K, Claes A, Struyf F. Swim training volume and shoulder pain across the lifespan of the competitive swimmer: a systematic review. *J Athl Train.* 2020;55(1).
5. Maglischo EW. *Primer for Swimming Coaches.* Hauppauge, New York: Nova Publishers; 2015.
6. Olbrecht J. Definitions and Principles of Training. In: Olbrecht J, ed. *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp (Belgium): F&G Partners; 2007.
7. Sein ML, Walton J, Linklater J, et al. Shoulder pain in elite swimmers: primarily due to swim-volume-induced supraspinatus tendinopathy. *Br J Sports Med.* 2010;44(2):105-113.
8. Olbrecht J. Determining Training Intensity and Content. In: Olbrecht J, ed. *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp (Belgium): F & G Partners; 2007.
9. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter & harder? *Br J Sports Med.* 2016;50(5):273.
10. Walker H, Gabbe B, Wajswelner H, Blanch P, Bennell K. Shoulder pain in swimmers: A 12-month prospective cohort study of incidence and risk factors. *Phys Ther Sport.* 2012;13(4):243-249.
11. Bak K. The Practical Management of Swimmer's Painful Shoulder: Etiology, Diagnosis, and Treatment. *Clinical Journal of Sport Medicine.* 2010;20(5):386-390.
12. Wolf BR, Ebinger AE, Lawler MP, Britton CL. Injury patterns in Division I collegiate swimming. *Am J Sports Med.* 2009;37(10):2037-2042.
13. Weldon EJr, Richardson AB. Upper extremity overuse injuries in swimming. A discussion of swimmer's shoulder. *Clin Sports Med.* 2001;20(3):423-438.

14. Gaunt T, Maffulli N. Soothing suffering swimmers: a systematic review of the epidemiology, diagnosis, treatment and rehabilitation of musculoskeletal injuries in competitive swimmers. *Br Med Bull.* 2012;103(1):45-88.
15. Soligard T, Schwellnus M, Alonso J-M, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med.* 2016;50(17):1030-1041.
16. Mountjoy M, Junge A, Alonso JM, et al. Consensus statement on the methodology of injury and illness surveillance in FINA (aquatic sports). *Br J Sports Med.* 2016;50(10):590.
17. Halson SL. Monitoring training load to understand fatigue in athletes. *Sports medicine (Auckland, NZ).* 2014;44 Suppl 2(Suppl 2):S139-S147.
18. Borresen J, Lambert MI. The Quantification of Training Load, the Training Response and the Effect on Performance. *Sports Med.* 2009;39(9):779-795.
19. Wallace L, Coutts A, Bell J, Simpson N, Slattery K. Using Session-RPE to Monitor Training Load in Swimmers. *Strength Cond J.* 2008;30(6):72-76.
20. Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. *J Sports Sci.* 2005;23(6):583-592.
21. Taylor KL, Chapman DW, Cronin JB, Newton MJ, Grill N. Fatigue Monitoring in High Performance Sport: a Survey of Current Trends. *Journal of Australian Strength and Conditioning.* 2012;20(1):12-23.
22. Foster C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc.* 1998;30(7):1164-1168.
23. Bourdon PC, Cardinale M, Murray A, et al. Monitoring Athlete Training Loads: Consensus Statement. *Int J Sports Physiol Perform.* 2017;12(Suppl 2):S2161-S2170.
24. Ferrari R. Writing narrative style literature reviews. *Medical Writing.* 2015;24(4):230-235.
25. Chase KI, Caine DJ, Goodwin BJ, Whitehead JR, Romanick MA. A Prospective Study of Injury Affecting Competitive Collegiate Swimmers. *Res Sports Med.* 2013;21(2):111-123.
26. Costa MJ, Bragada JA, Mejias JE, et al. Effects of Swim Training on Energetics and Performance. *Int J Sports Med.* 2013;34(06):507-513.
27. Díaz Gómez MM, Bocanegra Jaramillo OL, Teixeira RR, Espindola FS. Salivary surrogates of plasma nitrite and catecholamines during a 21-week training season in swimmers. *PloS one.* 2013;8(5):e64043.
28. Gough CE, Saunders PU, Fowlie J, et al. Influence of altitude training modality on performance and total haemoglobin mass in elite swimmers. *Eur J Appl Physiol.* 2012;112(9):3275-3285.

29. Green JM, Michael T, Solomon AH. The validity of ratings of perceived exertion for cross-modal regulation of swimming intensity. *J Sport Med Phys Fit.* 1999;39(3):207-212.
30. Psycharakis S. A Longitudinal Analysis on the Validity and Reliability of Ratings of Perceived Exertion for Elite Swimmers. *J Strength Cond Res.* 2011;25(2):420-426.
31. Pyne DB, Lee H, Swanwick KMJM, sports si, exercise. Monitoring the lactate threshold in world-ranked swimmers. *Med Sci Sports Exerc.* 2001;33(2):291-297.
32. Nicolas M, Vacher P, Martinent G, Mourot L. Monitoring stress and recovery states: Structural and external stages of the short version of the RESTQ sport in elite swimmers before championships. *J Sport Health Sci.* 2019;8(1):77-88.
33. Main LC, Warmington SA, Korn E, Gastin PB. Utility of the multi-component training distress scale to monitor swimmers during periods of training overload. *Res Sports Med.* 2016;24(3):269-280.
34. Atlaoui D, Duclos M, Gouarné C, Lacoste L, Barale F, Chatard J-C. The 24-h Urinary Cortisol/Cortisone Ratio for Monitoring Training in Elite Swimmers. *Med Sci Sports Exerc.* 2004;36(2):218-224.
35. Atlaoui D, Duclos M, Gouarne C, Lacoste L, Barale F, Chatard JC. 24-hr Urinary Catecholamine Excretion, Training and Performance in Elite Swimmers. *Int J Sports Med.* 2006;27(04):314-321.
36. Diaz MM, Bocanegra OL, Teixeira RR, Soares SS, Espindola FS. Salivary Nitric Oxide and Alpha-Amylase as Indexes of Training Intensity and Load. *Int J Sports Med.* 2013;34(01):8-13.
37. Elbe A-M, Rasmussen CP, Nielsen G, Nordsborg NB. High intensity and reduced volume training attenuates stress and recovery levels in elite swimmers. *Eur J Sport Sci.* 2016;16(3):344-349.
38. Hellard P Fau - Avalos M, Avalos M Fau - Hausswirth C, Hausswirth C, Pyne D, Toussaint JF, Mujika I. Identifying Optimal Overload and Taper in Elite Swimmers over Time. *J Sports Sci Med.* 2013;12(4):668-678.
39. Kilen A, Larsson TH, Jørgensen M, Johansen L, Jørgensen S, Nordsborg NB. Effects of 12 Weeks High-Intensity & Reduced-Volume Training in Elite Athletes. *PloS one.* 2014;9(4):e95025.
40. Mujika I, Chatard JC, Busso T, Geyssant A, Barale F, Lacoste L. Effects of training on performance in competitive swimming. *Can J Appl Physiol.* 1995;20(4):395-406.
41. Toubekis AG, Tsami Ap Fau - Smilios IG, Smilios Ig Fau - Douda HT, Douda Ht Fau - Tokmakidis SP, Tokmakidis SP. Training-induced changes on blood lactate profile and critical velocity in young swimmers. *J Strength Cond Res.* 2011;25(6):1563-1570.

42. Wallace LK, Slattery Km Fau - Coutts AJ, Coutts AJ. The ecological validity and application of the session-RPE method for quantifying training loads in swimming. *J Strength Cond Res.* 2009;23:33-38.

43. Collette R, Kellmann M, Ferrauti A, Meyer T, Pfeiffer M. Relation Between Training Load and Recovery-Stress State in High-Performance Swimming. *Front Physiol.* 2018;9(845).

44. García-Ramos A, Feriche B, Calderón C, et al. Training load quantification in elite swimmers using a modified version of the training impulse method. *Eur J Sport Sci.* 2015;15(2):85-93.

45. Pelayo P, I.F. M, Sidney M, Chatard JC. Blood lactate recovery measurements, training, and performance during a 23-week period of competitive swimming. *Eur J Appl Physiol.* 1996;74.

46. Norlander T, Archer T. Predicting Performance in Ski and Swim Championships: Effectiveness of Mood, Perceived Exertion, and Dispositional Optimism. *Percept Mot Skills.* 2002;94(1):153-164.

47. Grove JR, Main LC, Partridge K, et al. Training distress and performance readiness: Laboratory and field validation of a brief self-report measure. *Scand J Med Sci Sports.* 2014;24(6):e483-490.

48. Sperlich B, Zinner C, Heilemann I, Kjendlie P-L, Holmberg H-C, Mester J. High-intensity interval training improves VO(2peak), maximal lactate accumulation, time trial and competition performance in 9-11-year-old swimmers. *European Journal of Applied Physiology.* 2010;110(5):1029-1036.

49. Pugliese L, Porcelli S, Bonato M, et al. Effects of manipulating volume and intensity training in masters swimmers. *International Journal of Sports Physiology and Performance.* 2015;10(7):907-912.

50. Faude O, Meyer T, Scharhag J, Weins F, Urhausen A, Kindermann W. Volume vs. intensity in the training of competitive swimmers. *Int J Sports Med.* 2008;29(11):906-912.

51. Hopkins WG. Quantification of training in competitive sports. *Sports Med.* 1991;12(3):161-183.

52. Billat LV. Use of blood lactate measurements for prediction of exercise performance and for control of training. Recommendations for long-distance running. *Sports Med.* 1996;22(3):157-175.

53. Owles WH. Alterations in the lactic acid content of the blood as a result of light exercise, and associated changes in the co(2)-combining power of the blood and in the alveolar co(2) pressure. *J Physiol.* 1930;69(2):214-237.

54. Goodwin ML, Harris JE, Hernández A, Gladden LB. Blood lactate measurements and analysis during exercise: a guide for clinicians. *Journal of diabetes science and technology.* 2007;1(4):558-569.
55. Borg GA. Psychophysical bases of perceived exertion. *J Med sci sports exerc.* 1982;14(5):377-381.
56. Foster C, Daines E, Hector L, Snyder AC, Welsh R. Athletic performance in relation to training load. *Wis Med J.* 1996;95(6):370-374.
57. Borg G, Ljunggren G, Ceci R. The increase of perceived exertion, aches and pain in the legs, heart rate and blood lactate during exercise on a bicycle ergometer. *Eur J Appl Physiol Occup Physiol.* 1985;54(4):343-349.
58. Kurokawa T, Ueda T. Validity of ratings of perceived exertion as an index of exercise intensity in swimming training. *Ann Physiol Anthropol.* 1992;11(3):277-288.
59. McNair D, Lorr M, Droppleman L. Revised manual for the profile of mood states. Educational and Industrial Testing Service. Published 1992. Accessed.
60. Morgan WP, Costill DL, Flynn MG, Raglin JS, O'Connor PJ. Mood disturbance following increased training in swimmers. *Med Sci Sports Exerc.* 1988;20(4):408-414.
61. Fry RW, Grove JR, Morton AR, Zeroni PM, Gaudieri S, Keast D. Psychological and immunological correlates of acute overtraining. *Br J Sports Med.* 1994;28(4):241-246.
62. Kallus KW, Kellmann M. Burnout in athletes and coaches. In: Hanin YL, ed. *Emotions in sport.* Champaign, IL: Human Kinetics; 2000:209-230.
63. de Almeida MO, Hespanhol LC, Lopes AD. Prevalence of musculoskeletal pain among swimmers in an elite national tournament. *Int J Sports Phys Ther.* 2015;10(7):1026-1034.
64. Harrington S, Meisel C, Tate A. A cross-sectional study examining shoulder pain and disability in Division I female swimmers. *J Sport Rehabil.* 2014;23(1):65-75.
65. Ristolainen L, Kettunen JA, Waller B, Heinonen A, Kujala UM. Training-related risk factors in the etiology of overuse injuries in endurance sports. *J Sports Med Phys Fitness.* 2014;54(1):78-87.
66. Tessaro M, Granzotto G, Poser A, Plebani G, Rossi A. Shoulder pain in competitive teenage swimmers and it's prevention: A retrospective epidemiological cross sectional study of prevalence. *Int J Sports Phys Ther.* 2017;12(5):798-811.
67. Shephard RJ. Limits to the measurement of habitual physical activity by questionnaires. *Br J Sports Med.* 2003;37(3):197-206.
68. Shephard RJ. Limits to the measurement of habitual physical activity by questionnaires. *Br J Sports Med.* 2003;37(3):197.

69. Trost SG. Objective measurement of physical activity in youth: current issues, future directions. *Exerc Sport Sci Rev.* 2001;29(1):32-36.
70. Jacobs DR, Jr., Ainsworth BE, Hartman TJ, Leon AS. A simultaneous evaluation of 10 commonly used physical activity questionnaires. *Med Sci Sports Exerc.* 1993;25(1):81-91.
71. Lamonte MJ, Ainsworth BE. Quantifying energy expenditure and physical activity in the context of dose response. *Med Sci Sports Exerc.* 2001;33(6 Suppl):S370-378; discussion S419-320.
72. Montoye H. Measuring physical activity and energy expenditure. Champaign. *Human Kinetics, IL.* 1996.
73. Cummins C, Orr R, O'Connor H, West C. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine.* 2013;43(10):1025-1042.
74. Franco MI, Samuele MM, Aaron JC. Internal and External Training Load: 15 Years On. *Int J Sports Physiol Perform.* 2018;14(2):270-273.
75. Raglin JS, Turner PE. Anxiety and performance in track and field athletes: A comparison of the inverted-U hypothesis with zone of optimal function theory. *Personality and Individual Differences.* 1993;14(1):163-171.
76. Lavallee D, Thatcher J, Jones M. *Coping and emotion in sport.* Vol 1. London: Nova Science; 2004.
77. McKenzie DC. Markers of excessive exercise. *Can J Appl Physiol.* 1999;24(1):66-73.
78. Hanin Y. Iceberg profile. In: Eklund R, Tenenbaum G, eds. *Encyclopedia of Sport and Exercise Psychology*. Thousand Oaks: SAGE Publications, Inc.; 2014.
79. Hibberd EE, Myers JB. Practice habits and attitudes and behaviors concerning shoulder pain in high school competitive club swimmers. *Clin J Sport Med.* 2013;23(6):450-455.
80. Kellmann M, Kallus KW. *Recovery-stress Questionnaire for Athletes: User Manual.* Human Kinetics; 2001.
81. Green JM, McLester JR, Crews TR, Wickwire PJ, Pritchett RC, Lomax RG. RPE association with lactate and heart rate during high-intensity interval cycling. *Med Sci Sports Exerc.* 2006;38(1):167-172.
82. Ueda T, Kurokawa T. Relationships between perceived exertion and physiological variables during swimming. *Int J Sports Med.* 1995;16(6):385-389.
83. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitoring exercise training. *J Strength Cond Res.* 2001;15(1):109-115.
84. Robinson DM, Robinson SM, Hume PA, Hopkins WG. Training intensity of elite male distance runners. *Med Sci Sports Exerc.* 1991;23(9):1078-1082.

85. Williams JG, Eston RG. Determination of the intensity dimension in vigorous exercise programmes with particular reference to the use of the rating of perceived exertion. *Sports Med.* 1989;8(3):177-189.
86. Uusitalo AL. Overtraining: making a difficult diagnosis and implementing targeted treatment. *Phys Sportsmed.* 2001;29(5):35-50.
87. Achten J, Jeukendrup AE. Heart rate monitoring. *Sports Med.* 2003;33(7):517-538.
88. Buchheit M, Al Haddad H, Simpson BM, et al. Monitoring accelerations with GPS in football: time to slow down? *Int J Sports Physiol Perform.* 2014;9(3):442-445.
89. Larry RE. Exercise (Substrate Utilization and Endocrine Parameters). In: Larry RE, ed. *Textbook of Veterinary Physiological Chemistry.* Third Edition ed. Oxford, UK: Elsevier Inc; 2015:498-502.
90. Dennis SC, Noakes TD. EXERCISE | Metabolic Requirements. In: Caballero B, ed. *Encyclopedia of Food Sciences and Nutrition (Second Edition).* Oxford: Academic Press; 2003:2217-2222.
91. Gleeson M. Biochemical and immunological markers of over-training. *J Sports Sci Med.* 2002;1(2):31-41.
92. Krause S, Langrock M, Weiss M. Influence of seasonal variations in training loads on selected amino acids and parameters of the psychoimmunological network in a swimming team. *Int J Sports Med.* 2002;23(5):380-387.
93. Diaz Gomez MM, Bocanegra Jaramillo OL, Teixeira RR, Espindola FS. Salivary surrogates of plasma nitrite and catecholamines during a 21-week training season in swimmers. *PLoS One.* 2013;8(5):e64043.
94. Edmonds R, Burkett B, Leicht A, McKean M. Effect of chronic training on heart rate variability, salivary IgA and salivary alpha-amylase in elite swimmers with a disability. *PLoS One.* 2015;10(6):e0127749.
95. Kalva-Filho CA, Zagatto AM, Araujo MIC, et al. Relationship between aerobic and anaerobic parameters from 3-minute all-out tethered swimming and 400-m maximal front crawl effort. *J Strength Cond Res.* 2015;29(1):238-245.
96. Vandewalle H, Péérès G, Monod H. Standard Anaerobic Exercise Tests. *Sports Medicine.* 1987;4(4):268-289.
97. Rouard AH, Billat RP. Influences of sex and level of performance on freestyle stroke: an electromyography and kinematic study. *Int J Sports Med.* 1990;11(2):150-155.
98. Chambers R, Gabbett TJ, Cole MH, Beard A. The Use of Wearable Microsensors to Quantify Sport-Specific Movements. *Sports Med.* 2015;45(7):1065-1081.

99. Gerber M, Brand S, Lindwall M, et al. Concerns regarding hair cortisol as a biomarker of chronic stress in exercise and sport science. *J Sports Sci Med.* 2012;11(4):571-581.
100. Skoluda N, Dettenborn L, Stalder T, Kirschbaum C. Elevated hair cortisol concentrations in endurance athletes. *Psychoneuroendocrinology.* 2012;37(5):611-617.
101. Robson P. Elucidating the unexplained underperformance syndrome in endurance athletes : the interleukin-6 hypothesis. *Sports Med.* 2003;33(10):771-781.
102. Lakier Smith L. Overtraining, excessive exercise, and altered immunity: is this a T helper-1 versus T helper-2 lymphocyte response? *Sports Med.* 2003;33(5):347-364.

Table 1. Overview of employed parameters and respective monitoring method within swimming research, categorize external and internal training load.

Category	Parameter	Monitoring method	References
External load	Swim volume (m/wk; h/wk)	Real-life observation	10,25-27,34-37,39-45,48-50
		Self-reported	46,47
	Dry-land volume (h/wk)	Real-life observation	34,35,38,40
Internal load			
Physiological	Training HR (bpm)	Tracking device	29,30,36,42
	Blood LA (mmol/l)	Fingertip sample	27,34-36
		Earlobe sample	28,30,31,42,50
	(s)RPE	Self-reported (Borg's Scale 6-20; Borg's CR-10)	32,37,39,43,44,46,48,58
	Swimming pace	LA-velocity curve	38,40,41,45,49
Psychological	Mood state	Self-reported (POMS)	46
	Training distress	Self-reported (TDS)	33,47

Abbreviations: m = meter; wk = week; h = hours; bpm = beats per minute; LA = Lactate; TDS = Training Stress; RPE = Rating of Perceived Exertion; s-RPE = session RPE; POMS = Profile of Mood States.